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DOE-0303-FP
Revision 0

Experiences in Decontamination and Decommissioning of Former Plutonium Production Reactors at the Hanford Reservation

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

United States
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P.O. Box 550
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Experiences in Decontamination and Decommissioning of Former Plutonium Production Reactors at the Hanford Reservation

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U.S. Department of Energy-Richland
Operations Office

MAY 2003

Prepared for the U.S. Department of Energy
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Experiences in Decontamination and Decommissioning of Former Plutonium Production Reactors at the Hanford Reservation

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Abstract:

Nine nuclear reactors were built at the Hanford reservation for plutonium production from 1943 to 1964. Eight of the reactors were shutdown by 1971, and the last in early 1987. Since then, disposition of the reactors has been incorporated into the Hanford cleanup program. The objective is to transition the reactors from their existing state of minimal maintenance and upkeep into a safe condition that can be maintained for several decades.

This paper describes the decontamination and decommissioning (D&D) work performed on five of the nine reactors. Reactor systems and structures, including subgrade systems such as piping were removed. An enclosure was built over the defueled reactor block. The resulting structure is called the Safe Storage Enclosure and is intended to safely house the core for at least 75 years. A permanent disposition for the facility will be determined at that time. Numerous hazards have been encountered and safely handled during this work, including the discovery of over a dozen irradiated fuel pins in one storage basin.

This paper discusses how this work was integrated into the cleanup program and then moved through the D&D process. The goal is to facilitate site cleanup by quickly removing imminent hazards while not compromising safety standards during a time of reduced budgets and intense emphasis on efficiency. This paper demonstrates excellence in coordination of safety analysis and D&D field work that will soon place the reactors in a safe storage condition for several decades. Safety analysis and field programs, practices, and lessons-learned will be discussed. Efforts to convert B Reactor into a permanent museum will be briefly discussed.

Reactor History:

Nine reactors for plutonium production were built at the Hanford reservation from 1943 to 1964. The Manhattan Project selected the Hanford site due to favorable soil conditions for heavy construction, availability of water and electricity (both provided by the Columbia River, either directly from the River or via the then-just completed Grand Coulee Dam), and sufficient open space that would displace a minimum local population. Additional important siting criteria were that the reactors be spaced far enough apart so that an accident (e.g., a feared criticality explosion) at one facility would not damage another, nor would the radioactive plume pass over a large civilian city.[a]

Figure One shows the reactor locations at Hanford (e.g., B and C Reactors are at 100-B,C). The DR Reactor was located adjacent to the D Reactor. Two reactors, called K-East and K-West, are at 100-K.

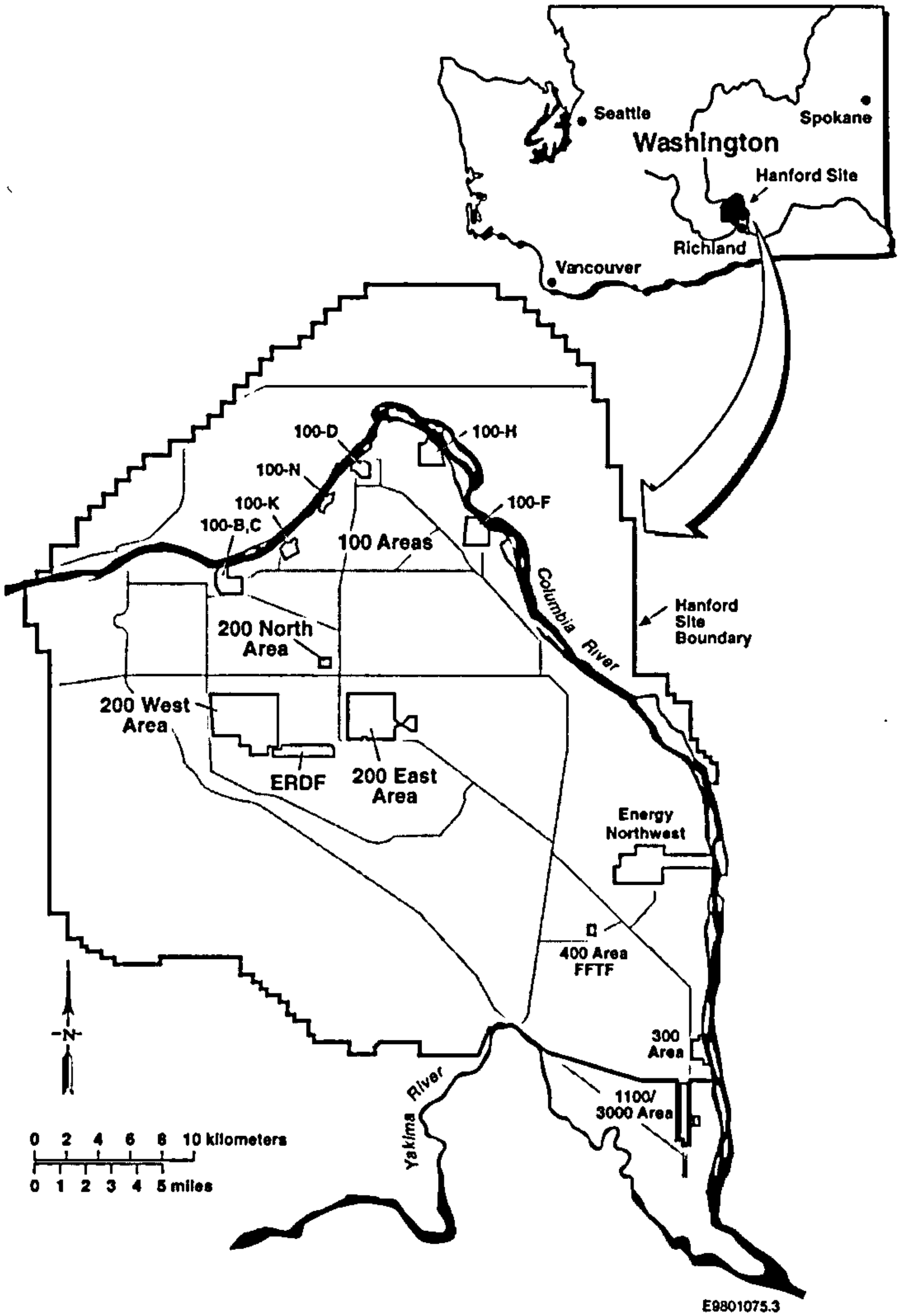
The Hanford site produced the plutonium (mostly from the B Reactor, the world's first production nuclear reactor) for the world's first and third nuclear weapons. Table One shows the production summaries for the nine reactors.[b]

Table 1
Plutonium Production, Hanford Site
1944- 1987

Reactor	Total Pu[1], Kg	Fuel-Grade Pu, Kg	Years of Operation
B	5,530	610	22
C	6,470	570	17
D	5,490	650	12
DR	3,840	50	14
F	4,500	55	20
H	4,140	99	15
KE	13,500	1,040	16
KW	12,800	1,790	15
N	11,000	8,170	22
Total	**67,300**	**13,000**	**153**

1- Total plutonium consists of both fuel grade and weapon grade plutonium production. Weapons grade Pu is considered to have < 6% Pu-240 content (i.e., is $\geq$ 94% Pu-239). Fuel-grade Pu has > 6% Pu-240 content and is generally not suitable for use in weapons. Fuel-grade Pu can be mixed with uranium to make MOX fuel.

FIGURE ONE


Seattle
Spokane
Washington
Hanford Site
Richland
Vancouver
100-D
100-H
100-N
100-K
100-F
100-B,C
100 Areas
Columbia River
Hanford Site Boundary
200 North Area
200 West Area
ERDF
200 East Area
Energy Northwest
400 Area FFTF
300 Area
1100/ 3000 Area
Yakima River
N
0 2 4 6 8 10 kilometers
0 1 2 3 4 5 miles
E9801075.3

Experiences in D&D of Production Reactors at Hanford

Plutonium continued to be the principle Hanford product during the production period, 1944-1989. However, incidental weapons-related radionuclides were also produced during this time:

- tritium;
- U-233 from thorium irradiation;
- polonium production for early bomb initiators;
- neptunium, and other minor materials.

Throughout the period, the Atomic Energy Commission forsook innovation for the sake of the tried-and-true, and reactor design remained remarkably unchanged, except for size and some technical improvements. While not particularly efficient, the reactors were reliable and could guarantee steady production. They were single-pass water cooled, graphite-moderated cores. Fuel pins were inserted into the pile horizontally, inside process tubes through which cooling water flowed and then discharged to the Columbia River, sometimes after a short holding period.[2] Reactor power level was controlled by horizontal control rods. Table Two summarizes important reactor features.

Reactor fuel consisted of slightly enriched (< 3%) uranium held in thin cylinders, from 9 to 27 inches long. The fuel was manufactured on-site in the 300 Area from yellow-cake. Hanford produced about 60% of the nation's plutonium stockpile.

While assuredly not a consideration at the time, the modular reactor facility design would later aid D&D. The facility consisted of three major areas: the reactor pile, radiation and thermal shields, fuel rod process tubes, and safety and control systems; the irradiated fuel storage pool; and the support building, containing the control room, ventilation equipment exhausting to a stack, repair rooms, and offices. The reactor building was reinforced concrete and concrete block about 250 by 230 by 95 feet high. The graphite pile was not a perfect cube, being higher than it was long. The individual graphite blocks, 4 1/4 inches square by 44 1/2 inches long, were stacked in an interlocking crisscross pattern.

Figure Two shows a typical reactor facility. Note the economy of layout--basically, the facility is connected boxes. The design emphasized speed of construction and functional operation. There was no containment system for the reactor.

As can be seen in Table Two, reactor power level, except for N Reactor, increased dramatically over facility life. This was the result of operational and technical improvements. However, the higher power levels necessarily entailed higher operating temperatures which led to the onset of fuel pin failures in the late 1940's. Fuel failure is rupture of the cladding, resulting in release of fission products into the cooling water stream. If there was a small leak in that process tube, pin

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2. N Reactor used a closed loop cooling system, and did not discharge water directly to the Columbia.

failure resulted in contamination of the graphite pile itself.

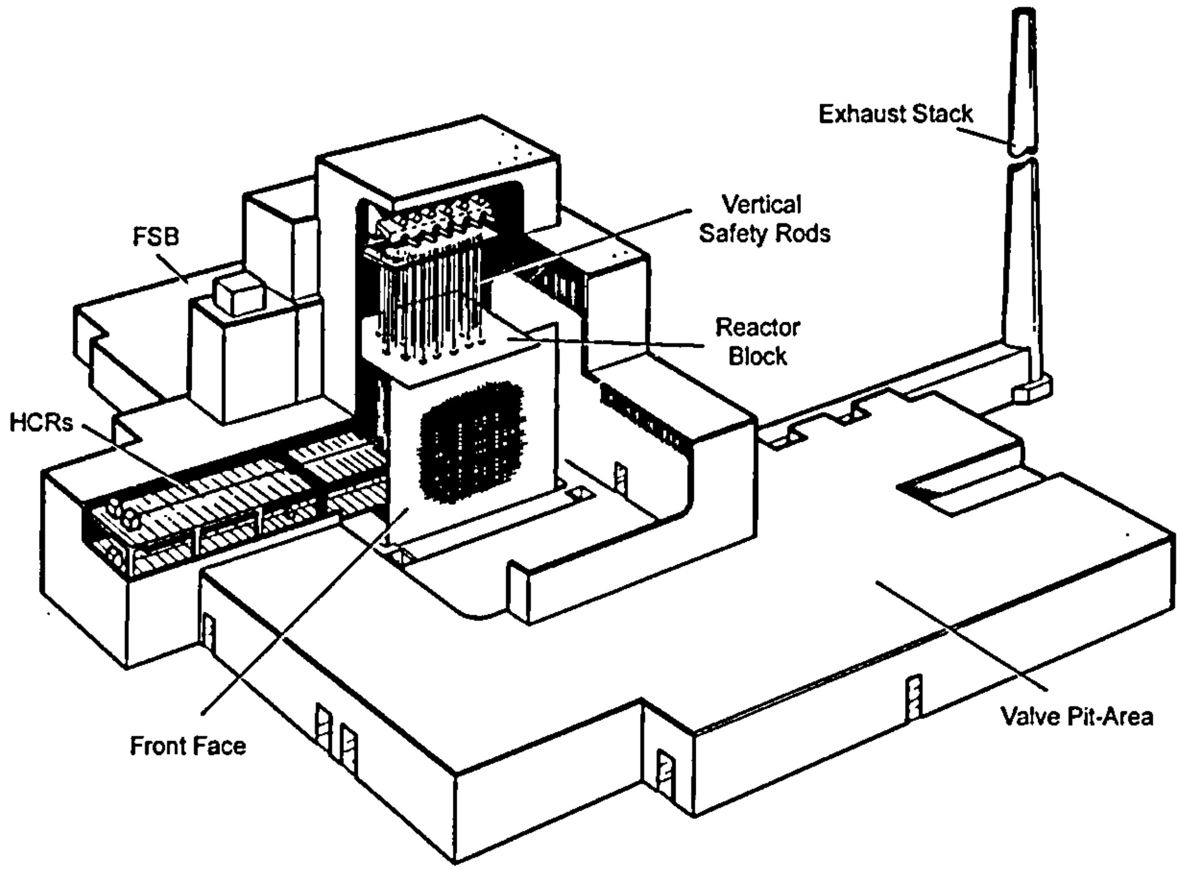

FIGURE TWO

Table 2
Hanford Reactor Features

	B	C	D	DR	F	H	KE	KW	N
Power Level, Mwt Design/ Final Operating	250/ 1,940	750/ 2,310	250/ 2,005	250/ 1,925	250/ 1,935	250/ 1,955	1,800/ 4,400	1,800/ 4,400	4,000/ same[3]
Period of Operation	9/44- 2/68[4]	11/52- 4/69	12/44- 6/67	10/50- 12/64	2/45- 6/65	10/49- 4/65	4/55- 1/71	1/55- 2/70	12/63- 1/87
Pile Dimensions (Ft):									
Side to Side	36	36	36	36	36	36	41	41	33
Bottom to Top	36	36	36	36	36	36	41	41	33
Front to Back	28	28	28	28	28	28	33.5	33.5	39
Pile Weight, lbs	3.8E+06	3.8E+06	3.8E+06	3.8E+06	3.8E+06	3.8E+06	5.7E+06	5.7E+06	3.6E+06
Thermal Shield Weight, lbs	2.2E+06	2.2E+06	2.2E+06	2.2E+06	2.2E+06	2.2E+06	2.2E+06	2.2E+06	2.2E+06
Bio Shield Weight, lbs	9.8E+06	9.8E+06	9.8E+06	9.8E+06	9.8E+06	9.8E+06	9.8E+06	9.8E+06	9.8E+06
#, Process Tubes	2004	2004	2004	2004	2004	2004	3220	3220	1003
#, Horizontal Control Rods	9	15	9	9	9	15	20	20	84
#, Vertical Control Rods	29	44	29	29	29	45	41	41	107

[3]- In terms of thermal power, N Reactor was the largest reactor ever built.

[4]- B Reactor was shutdown for two years from March, 1946 to June, 1948 in order to minimize swelling of the graphite pile, which was a serious operational problem at the time.

Experiences in D&D of Production Reactors at Hanford

The first significant cladding failures occurred in 1951, coincident with higher power levels and temperatures which caused cladding blisters, swelling, and eventually rupture. Prior to 1951, there were only five recorded pin failures. There were 115 in 1951. On average, there were 228 failures per reactor through 1963, or 18 per reactor per year.[5]

Interregnum

Eight of the reactors were shutdown by 1971, and the last, N Reactor, was taken out of service in early 1987. As part of the shutdown process, some attention was given to future D&D, although there was no firm understanding at that time that the reactors would never operate again. Shutdown consisted of the following tasks:

- the horizontal control and vertical safety rods were fully inserted;
- the process tubes were defueled and then rodded to ensure no fuel pins remained in them. Verifying that the tubes were clean was the single most important act for future D&D, saving considerable worry later on that irradiated fuel pins might have been inadvertently left in the pile;
- the cooling water system was shutdown. The process tubes were then blown out to minimize corrosion and capped. However, the air blow wasn't sufficient to completely dry the tubes, which were not checked in the years since;
- pressure instrument lines were drained and blown dry. Temperature indicators were isolated;
- the fuel storage basin was drained.

An asphalt fixative was applied to the lower fuel storage pool walls and floor at some facilities (e.g., D Reactor) to reduce the spread of contamination. However, this was not down at all facilities, apparently due to cost. Some of the basins were covered with wood planking to prevent falls and the migration of contamination from the basin to the operating floor. A few pools (B and D) were thoroughly cleaned.

For whatever reason, the fuel storage basins for F and H Reactors were filled in (with dirt, sand and rock) after being about 80% drained. Neither basin was seriously cleaned beforehand. This act would seriously complicate D&D work a generation later.

Thereafter, the reactors were semi-abandoned in a state of minimal upkeep and attention.

5- 2,092 documented cladding failures occurred from 1948 through 1969.

Structural deterioration continued unchecked. A worker fell to his death at F Reactor in 1992 when the reactor building roof gave way under him during an inspection.

Evolution of a Disposal Strategy

A comprehensive (and comprehensible) Hanford cleanup strategy began to emerge in the early 1990's. With it necessarily came priorities, driven by facility hazards (real or perceived). It became clear that less hazardous sites, like the reactors, might not be addressed for a while. Ultimate disposal of the production reactors was analyzed in an environmental impact statement, which DOE issued in December, 1992.[c] The corresponding Record of Decision appeared in September, 1993.[d] The EIS did not consider N Reactor, which had not been officially decommissioned when the EIS was started (1989). B Reactor--the world's first production reactor--was placed on the National Register of Historic Places in 1992 and may be turned into a museum, rather than demolished.

The EIS considered several disposal options:

- Safe storage followed by one-piece removal.
  This consisted of a safe storage period during which surveillance, monitoring, and maintenance continued (for 75 years or so), followed by transport of the reactor block (in one piece on a large tractor something like that used for the space shuttle) to a burial site in the 200 West area of Hanford.

  This option was estimated to cost $235 million (1990) and involve 51 man-REM of exposure.

  The worst case analyzed accident was dropping of the reactor pile during transport, which resulted in estimated population dose of 300 person-REM, which was considered negligible.

- No action.
  Surveillance, monitoring, and maintenance continued under existing circumstances for an indefinite period.

  This option was estimated to cost $44 million (1990) and involve 24 man-REM of exposure.

  No accidents were analyzed.

- Immediate one-piece removal.
  This consisted of immediate demolition of the facility and burial of the pile.

This option was estimated to cost $228 million (1990) and involve 159 man-REM of exposure.

The worst case analyzed accident was dropping the reactor pile during transport. The consequences were similar to the first option.

- Safe storage followed by piece by piece removal.
  This option is similar to the first, except that the reactor pile is removed piece by piece, rather than in one (big) effort.

  This option was estimated to cost $311 million and involve 532 man-REM of exposure.

  The worst case analyzed accidents were a severe storm during dismantlement and a fire involving a rail car assumed to be carrying pieces of the pile. The fire had the worst consequences, 800 man-REM.

- In-situ burial.
  This option prepared each reactor block for entombment under dirt and an engineered barrier. Contamination is fixed in place. Structures are removed down to the top of the reactor block. Then, the remainder is buried under at least 15 feet of dirt and a barrier to prevent water intrusion is put into place.

  This option was estimated to cost $193 million (1990) and involve 33 man-REM of exposure.

  No accidents were analyzed.

Because the first option removed the piles from the location near the Columbia River, had no significant environmental impact, involved less dose and was less expensive than piece-by-piece pile removal, it was selected for implementation.[6] However, initially, nothing was done at the reactor sites.

Consistent with the ROD, the reactors would continue in whatever state they happened to be in for many years, even decades, to come. Precisely what "safe storage" constituted was not well defined. As described in the EIS the term meant performing structural and component repairs to ensure safety and security. Important systems (e.g., electrical distribution, fire detection, and

6. This storage period accounts for the exposure differences (108 man-REM) between the first (preferred) and the third (immediate removal) options.

radiation monitors) would be upgraded as necessary. The EIS assumed a storage period of 75 years. This inevitably meant that the facilities would also have to be maintained for this rather long period. However, maintenance requires money. The EIS estimated $44 million, probably a conservative estimate. As the time line for cleanup strategy extended, budget forces pressed in, squeezing Hanford allocations tighter and causing every expenditure to be questioned, particularly embedded overhead costs like maintenance of deactivated defueled facilities. It was realized that a great deal of money could be saved if the reactor facilities were reduced to a state requiring the least upkeep while ensuring safety. This idea was termed "mortgage reduction"--reducing long term costs of existing facilities to a minimum.

Equally pressing was the need to cleanup the site, and show demonstrable progress at doing so. There were few better ways to achieve this at Hanford than tearing down the large obvious reactor facilities, which often included highly visible support structures like water towers and stacks.

To reduce costs, to free up money for more pressing cleanup priorities, and to show obvious cleanup progress, the reactor facilities would be placed in a configuration requiring the least upkeep. This condition was called "Interim Safe Storage."

The Interim Safe Storage (ISS) Concept

The purpose of the ISS was two-fold: remove as much of the hazardous facility as possible, while adequately protecting what remained for up to 75 years. The intent was to eliminate hazards rather than simply confine or mitigate them. The ISS would reduce the reactor facility to a minimally hazardous structure that posed the least risk to personnel and the environment for the next seven odd decades. The remaining radiologic inventory (mostly in the reactor block) would decay to make its later removal less hazardous.

Table Four shows an approximate inventory of the major radionuclides for a typical reactor block. (The word "approximate" cannot be overemphasized.) Note the substantial reductions that occur during the 75 year decay period prior to final disposal. The other radiologic hazard in the facility is fixed contamination and smearable low-level activity around the block.

Table 3
Approximate Major Radiologic Inventory for a Typical Reactor Block

Radionuclide	Inventory, Ci March, 1998	Inventory, Ci March, 2073
H-3	3,700	54
Cl-36	34 (est)	34
Co-60	1,400	.08
Sr-90	400	67
Cs-137	22	3.9
Ba-133	15 (est)	.1
Eu-152	21 (est)	.4
Eu-154	7.3 (est)	.02
Pu-238	4	2.2
Pu-239/240	3.3	3.3
Pu-241	43	1.7
Am-241	4	3.6
Cm-244	.1	.017

A hazard's significance was determined largely by its radiologic content, although some serious hazards were purely industrial.[7] The major radiologic hazard is the reactor block itself, which had an unknown (but presumed significant) radiologic inventory. Consistent with the EIS, the pile would be enclosed within a partially existing, partially new structure called the Safe Storage Enclosure (SSE) and not further disturbed. The SSE is composed of the existing heavily reinforced concrete shield walls enclosing the block, and a new roof and siding mated to the walls.

Facility structures outside the reactor shield walls, including the rod room, ventilation stack, and

7. For example, industrial safety drove the need to remove the large cooling water piping buried under the reactor and running to the Columbia. This piping could collapse underfoot in the coming years, creating a serious hazard to personnel.

control room, would be removed (demolished). The fuel storage basin would be removed and the area refilled with clean dirt to grade. Old floor drains would be plugged. Underground piping, including the large cooling water lines, would be removed. In the end, only about one-third of the original facility would remain, essentially the concrete shell housing the block itself.

A new sloped sheet metal roof anchored to the shield walls and connecting siding would be built over the reactor block. Minimal use was made of flashing joints, to reduce future leakage. Existing penetrations into the reactor block would be sealed.

Surveillance lighting (and a new power supply) would be added.

Because the existing ventilation system would be totally demolished, two HEPA-filtered exhaust ports were provided at ground level near the entrance. The primary concern was radon buildup between inspections. A portable exhauster can be connected to the ports and the ISS ventilated (air is induced through other installed ports) prior to entry. When not used, all ports are sealed with bolted flanges.

Table Four provides the codes and standards used in the ISS design. Note the extensive use of standard construction codes and UBC criteria.

Table 4
SSE Design Codes and Standards

Feature	Reference	Criteria
Roof Snow Load	ANSI/ASCE 7, Section 7	20 lbs/sq-ft
Roof Live Load	ANSI/ASCE 7 and UBC	20 lbs/sq-ft
Roof ash fall	None	24 lbs/sq-ft
Wind Load	ASCE 7-95, Figure 6	85 MPH with 3 second gusts at 33' above the ground in Exposure Category C
Seismic Load	UBC	Seismic zone 2B (.178 g horizontal, .115 g vertical)
Structural Steel	AISC Manual of Steel Construction, UBC	N/A
Concrete pours	ACI-318	N/A
Ventilation	ASHRAE	N/A
Tornado	None	Not considered to be a credible hazard

Lightning	NFPA 78	N/A
Electrical	NEC	N/A

Access into the SSE is through a steel plate door welded closed for security. In an emergency, the fire department can cut the door open with a saw.

The significant long term hazards to the SSE are water intrusion and fire. Because flammable material would be removed, fire was not considered a serious hazard. Therefore, smoke detectors were not installed. Two low maintenance heat detectors (RTD types) are provided at different parts of the SSE. A water level switch was installed at the lowest level to detect leakage. All three sensors are connected to a monitor system and the signal sent to a manned alarm facility at Hanford.

Preparation of Safety Analysis in Support of the ISS Concept

From the beginning, the D&D project sought to streamline the safety documentation effort without compromising actual safety. To that end, instead of a safety analysis report, an auditable safety analysis (ASA) would be prepared.[8] An ASA contains the elements typically found in a Basis for Interim Operation (BIO) safety analysis:

> a detailed facility description, operating history, authorized work (demolition and ISS construction) description, hazards inventory, hazards analysis, accident analysis, and a listing of the safety controls, including programmatic controls.

However, utilizing an ASA-type safety document required finding that the facility's hazard classification was Radiological, i.e., less than Haz Cat Three. Hazard classification is a two step process--preliminary (initial) and final hazard classification.[f] The PHC is determined by inventory. And therein lay a significant problem: DOE did not believe the source term (material at risk) of a reactor facility was well known.

Aside from residual loose surface and airborne contamination typically to be expected in a former production facility, significant radiologic inventory is in: the reactor thermal shield, the bio shield, the process tubes, and the graphite pile, which constitute the reactor block, the rod control system, and the fuel storage basin. The reactor block had a much greater inventory, even considering the probability that irradiated fuel might be in the dirt filled storage basins.[e]

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[8]- A general description of an auditable safety analysis is contained in Section 5.2 of *Hazard Baseline Documentation*, DOE-EM-STD 5502-94, August, 1994. This standard was in use at conception of the ISS project, but has since been discontinued after issuance of 10 CFR 830, Subpart B.

Experiences in D&D of Production Reactors at Hanford

In the mid 1980's, the site contractor at the time prepared a study of the anticipated reactor block inventory. Following a detailed technical review of that document, DOE believed the pile inventory was suspect for the following reasons:

- the study applied correction factors to the activation product inventories (eg, Co-60) to account for varying reactor flux. However, no correction was applied for the differences in local pile flux level which could easily exceed variations in total power levels. Correct factors could not be reconstructed due to inadequate operational records from the time.

- The basis for the pile inventory essentially rested on four core samples taken from the DR Reactor in the 1970's. The study assumed that the graphite inventory of the other reactors was identical to DR. There was no basis for this assumption.

- The analysis of the core samples from DR Reactor did not determine the concentration of either Pu-241 or Cm-244, although both should have been present. This was apparently a simple oversight in the sampling data quality objectives at the time.

- A single concentration for Am-241 was obtained from one DR core sample and that value was assumed constant across the entire pile. A single sample is not adequate.

Reviewing the DR core data, it was obvious that the principal contributor to inventory is fission product and TRU contamination. Such contamination is a function almost exclusively of the number of coincident fuel pin/process tube failures experienced by that reactor during its operation. There is no means of determining the number of such failures. The samples from DR clearly show at least two fuel pin contaminations in the four samples taken. Clearly, significant contamination of the graphite from fuel pin/process tube failures should be expected. Thus, the radionuclide inventory inside the core is much higher than predicted. However, as stated, there is no means to estimate the actual contamination, except for DR. The unique operational history of each reactor along with the unpredictable failure characteristics of the process tubes themselves makes any such estimates strictly conjectural. Process tube failures (apart from pin failures) would be a function of water chemistry control, manufacturing defects, operating practices (testing or experiments), local power level and temperature control, size and location of the respective leaks, and many other variables that cannot be recovered or estimated with any certainty now.

Fission of tramp uranium in the pile carbon blocks and fuel cladding would contribute a minor additional amount. Therefore, the isotopic inventory of the reactor core is unknown.

A better estimate was made of activation products (e.g., cobalt-60), based on composition of the various metals used and the assumed neutron flux. The vast majority of the Co-60 was believed located outside of the graphite core in the thermal shield, process tubes, and rod control system.

This of course left the safety analysis in a major quandary: with the isotopic inventory unknown, how could the facility's hazard category be determined? Further, if the hazard category was not known, how could the rigor, depth, and content of the attendant safety analysis be determined?

DOE solved this conundrum by the simple expedient, consistent with Standard 1027[f], of segmenting the facility and placing prohibitions on any work which could violate the reactor block. In essence, the pile was separated from the remainder of the facility and placed off-limits to intrusive work which could disturb its unknown content. This was easily accomplished since thick concrete and steel shields surround the core. No work was allowed which could in any way damage the reactor biologic and thermal shields or intrude into the pile through connecting piping. Once the block was segmented from the facility, the remaining inventory could be determined with acceptable accuracy.

However, since F and H spent fuel storage basins had been filled in with sand, their contents could not be surveyed accurately and were unknown. What was believed at the time to be a conservative assumption was then made that both basins held five irradiated fuel pins, each.

An inventory of major radionuclides from a typical facility is shown in Table Five. Note the minuscule amounts of radioactive material compared to other hazardous agents.

Table 5
Typical Hazardous Material Inventory
Former Production Reactor Facility[9]

Material	Inventory (Ci/ Lbs)	Haz Cat 3 TQ's (Ci)
Co-60	1430 Ci (1.3 g)	280
Sr-90	400 Ci (2.9 g)	16
Cs-137	22 Ci (.25 g)	60
Pu-238	4 Ci (.23 g)	.62
Pu-239/240	3.3 Ci (53 g, Pu-239)	.52

9. Only radionuclides important to safety analysis consequences are shown (see Table 3). Other radioisotopes are present (e.g., C-14, Cl-36). However, they are not significant in calculating accident releases, as their respective dose conversion factors (respirable dose) are extremely low.

Experiences in D&D of Production Reactors at Hanford

Material	Inventory (Ci/ Lbs)	Haz Cat 3 TQ's (Ci)
Pu-241	43 Ci (.42 g)	32
Am-241	4 Ci (1.2 g)	.52
Lead	189,000 lbs	NA
Mercury	80 lbs	NA
Asbestos	150,000 lbs	NA
PCB	750 lbs	NA

As can be seen, even with segmentation, the facility inventory exceeds the TQ's for several radionuclides. Segmenting the reactor block from the remainder of the facility did not allow downgrading the facility to Radiological. The corresponding facilities were therefore given preliminary hazard categorizations (PHC) of Nuclear, Haz Cat Three. Standard 1027[f] states that a SAR consistent with DOE order 5480.23 (specifically, paragraph 8.b, "Scope and Content of Safety Analysis Reports") is required.

Alternative direction was provided to the contractor to develop a hazards analysis and the bounding accidents and release consequences. The outcome would be used to find the facility's FHC. If it was below Category Three--i.e., Radiological--then the safety analysis would follow the form and content guidance of an ASA. In effect, this direction "front loaded" determination of the FHC with the expectation of avoiding the attendant extensive analysis and program descriptions required for full SAR's (e.g., criticality analysis, derivation of technical safety requirements, programmatic chapter discussions, etc). However, if the FHC remained Haz Cat 3, a SAR consistent with DOE Order 5480.23 would be required. This direction assumed that criticality was incredible and that no accident releases would require on-site emergency planning activities.

Determining the FHC prior to commencing preparation of a full SAR was not inconsistent with direction provided in DOE Order 5480.23, "Nuclear Safety Analysis Reports". The Order allows considerable latitude in the sequence of events to SAR preparation. Program direction did not violate DOE safety analysis requirements in existence at the time. However, as further discussed below, the hazard categorization process was not fully consistent with Standard 1027, either.

For F Reactor, DOE accepted a FHC of non-nuclear, Radiological. The significant inventory was almost entirely due to the (assumed) five irradiated fuel pins in the storage basin. Contrary to the guidance in Standard 1027, the FHC was not based on radionuclide inventory. Rather, an interpretation was made to the Standard based on how the TQ limits in Table A-1 were derived. Exposure to Category Three TQ's results in a 10 REM whole body dose using an EPA model assuming a distance of 30 meters from the release point and a 24 hour exposure time. Turning this methodology around, if the worst-case accident dose was shown to be < 10 REM at 30 meters, regardless of the facility's inventory compared to Table A-1, then the facility could be considered below Haz Cat Three, i.e., Radiological. If the facility release did not exceed the criteria by which the Table was created, then the limits in the Table no longer matter. At the time, some precedence for this interpretation existed.[10]

Accident release calculations showed that worst-case dose was 3.5 REM to a receptor thirty meters away. Therefore, because the release did not exceed 10 REM, F Reactor was categorized as Radiological.[11]

D Reactor was also categorized as Radiological based on the following conditions:

- criticality was not credible;
- emergency evacuation of nearby facilities would not be required;
- no irradiated fuel pieces would be encountered during D&D; and
- the hazards analysis did not credit either safety-class or safety-significant SSC's to prevent or mitigate the release of hazardous material.

C and DR Reactors were categorized in a similar manner to D.

An FHC of Radiological for the Reactors is supported by the following additional considerations:

1. Segmentation: Sufficient segmentation of core contaminants away from the rest of the facility exists. The contaminants inside the block are isolated inside the thermal and bio shields which are inviolate by specific project controls.

2. Dispersibility: Most of the radionuclides likely adhere to graphite in the central portion of the core. For the most part, reactor power was concentrated in the

10- See final paragraph of memorandum, R.L. Black, DOE-EH, to C.M. Steele, LANO, "Request for Interpretative Guidance on Final Hazard Categorization of the Sigma Complex", dated 2/25/1999. With the subsequent issuance of 10 CFR 830, Subpart B, this interpretation is no longer valid.

11- EH-1 recently issued a Nuclear Safety Technical Position, NSTP 2002-2, 11/13/02, addressing the 10 REM @ 30 meters interpretation of Standard 1027. 10 CFR 830, Subpart B had not been issued at the time the F Reactor safety analysis was prepared (1998). The methodology described here (10 REM @ 30 meters, etc) used to determine the FHC is not consistent with Subpart B. The NSTP states that previously existing interpretations to Standard 1027 are no longer valid.

central region. Therefore, most cladding failures likely occurred there and less TRU/fission product contamination is expected around the core perimeter. No mechanism exists for migration of contamination from the central graphite blocks toward the periphery. As such, there is little chance for release of contaminants except by catastrophic failure of the pile itself. Such a release would require (from outward to inward) failure of the reactor shell, failure of the steel and masonite bioshield, and failure of the steel thermal shield followed by breakup and collapse of the graphite blocks. The analyzed earthquake could not cause such a release.

3. Form: The pile contaminants are solids and not gases. Release requires reducing the graphite to powder and then dispersing it. The graphite core could not be completely contaminated. Rather, irregular spots of contamination exists in the blocks. Therefore, substantial release of contamination would require substantial damage of the graphite, which was judged beyond extremely unlikely.

Standard 1027[f] does not specifically allow such factors to be used to downgrade a hazard category from Three to Radiological. As such, categorization of the Reactors was not strictly consistent with the Standard. Nevertheless, DOE believes the safety analysis for each facility adequately bounded the D&D work.

While it may seem that the considerable effort to determine the pile inventory (considering fuel pin failures) was similar in the end to swatting gnats, DOE looks at the matter historically. Three generations will pass before final disposal of the reactor blocks occur. The author believes that one-piece removal will not be the option selected seventy-five years from now. By stating unequivocally that what is in the piles is simply not known (and documenting this uncertainty in the facility safety evaluation reports) a warning is given to the future to be careful and to not accept glib assertions from some future contractor that everything is--or will be--fine.

D&D Field Work

The actual process of constructing the SSE and placing a reactor facility into ISS is referred to in the field as "cocooning." As part of the prep work for ISS, an inspection was made of each reactor facility and a hazards inventory prepared. A preliminary hazards analysis (PHA) was then performed. The controls for D&D, derived from the PHA, rested heavily on programs for rad and fire protection, worker (industrial hygiene) safety, emergency response, and conduct of operations. These programs were implemented by field work procedures. Thus, from the beginning, the safety analysis was directly tied to the work procedures at the field level. This practice cut the length of paper trails and ensured workers were fully aware of the safety analysis's control measures.

When identified, specific (not programmatic) control measures in the ASA were crisply stated so that no misunderstanding of their intent or meaning would occur. Verbatim examples of such measures are:

- no propane will be permanently installed;
- no gases [e.g., acetylene, propane] will be stored within the facility;
- personnel must evacuate during a fire in the basin;
- if fuel rods are found, work will stop in that area and barricades established to protect workers. No retrieval will be done without specific DOE approval.

However, in retrospect, a more clear control should have been placed on the amount of wood (combustible material) allowed to be in the storage basins. The ASA did not address that issue well, and that oversight slowed field work when clarifications were needed.

"Tail-gate" safety meetings with the craft workers that reviewed pertinent safety issues with the day's planned activities helped to underscore the safety programs and controls.

The radiological surveys conducted preparatory to commencing D&D took considerable time. There was virtually no accessible survey records from the late 1960's and early 1970's for the basins. Original construction prints (when available) were often inaccurate or did not show important detail. Later design changes were seldom shown. An AIL gamma camera was used during the surveys. Basin debris (fuel pin baskets, fuel spacers, and scrapped process tubes) contributed to the radiation field. With the dirt in them, the F and H storage basins were impossible to characterize and the inventory (amount of junk on the floor) was unknown. Experience showed that manual surveys obtained more accurate results and were quicker.

Highest general area radiation levels were 10-20 mREM/hr. A few hotshots (> 100 mREM/Hr) existed in the rod rooms and around the reactor block. The basins had the highest accessible radiologic inventory (no work was done with the reactor block). Fuel pins were found to read 10-110 REM/Hr, on contact. Fuel spacers read up to several R/Hr. Scraped process tubes read up to 300 mREM/Hr. Spots of contamination up to 400 mREM/Hr existed in F and H basins. Field workers found that the basins were the biggest radiological problem, whereas the reactor block and inner rod room was easy to work in and easy to survey.

The D&D contractor (Bechtel Hanford, Inc) developed an innovative survey system, called the Advanced Characterization System (ACS) to perform radiologic surveys. ACS is designed to minimize the quantity of low-level radioactive waste generated during D&D. The system integrates several instruments to identify, characterize, and quantify radioactive contamination. Since most of the equipment is automated, the survey process is not labor intensive. ACS was first used on the D Reactor. The survey was completed by a four man team in six weeks. Such a survey would otherwise have taken a much larger crew considerably longer. About half of the facility was found to be uncontaminated. The survey provided information to determine appropriate work controls and personnel protective features. The pilot deployment in D Reactor saved over $1 million in survey time, more than twice the $590,000 cost of the system. ACS was again used in H Reactor, with the survey taking only three weeks. Project savings were calculated to be $728,000.[12]

Cement block walls were removed by saw and jackhammer. Sometimes the blocks were dumped off the edge of the building and then carried away. However, care was taken to ensure the falling blocks could not collapse some underground structure. A wrecking ball was never used. Concrete fracturing using explosives is being considered for thick shield walls around the former vent fan room at H Reactor, which did not have a significant radiologic inventory. The explosives would fracture the concrete, resulting in a teetering collapse, and would not shatter (pulverize) it.

Contamination atop the reactor block was fixed in place with paint. Unfortunately, the paint later peeled due to water leakage through the old roof.

Basin excavation required several novel tools to meet its unique challenges. Most of the dirt was removed by a large, manually controlled front end loader. However, the size of its bucket prevented it from getting into small areas. Also, it was not adequate to handle areas of high radiation, which were exposed as the dirt and sand were removed. A BROKK remote control track-hoe excavator, essentially a small tractor tread front end loader, was purchased for hard-to-get-to areas and hot spots. To control the BROKK, workers mounted a high resolution camera on the unit and three more cameras in the basin itself. The images were sent to a central control station adjacent to the basin.

The BROKK was built in Sweden, which presented several problems with parts made for European fittings. The unit's hydraulic hoses tended to snag in the thick (#11 and #12) rebar used for reinforcing the basin walls. Rebar was a major headache. After several aggravating breakdowns, the hydraulic system was reconfigured with American fittings, which greatly aided subsequent repairs. For ALARA considerations, a crane lifted the unit out of the basin when repairs were needed. A special tool called a scraper, a flat plate similar to a shovel, could be fitted in place of the bucket to clear out dirt and other debris.

A BROKK is shown in Figure Three. Note the uncertain operating surface which required deploying the stabilizer arms. (The short walls are called stem walls, and divided the storage basin floor into long sections, apparently for criticality control when pins were stored there.) Also note the rainwater in the basin, which had to be pumped out manually.

As things turned out, the direction to attack dirt removal from the basins proved to be wrong. The direction chosen was from the side. Attack should have been straight in from the end, which would have involved less reach for the excavator and given more room to work along the basin

12. For more information on the ACS system, readers may contact Douglas Duvon of BHI, 509-372-9182.

sides.

As dirt removal from the F and H basins proceeded, an unexpected means of contamination migration occurred. Dust devils are common in the mid-Columbia. As the basins are fairly large, the mini-cyclones would occasionally set down inside the basins and carry contaminated dust aloft onto the adjacent exposed reactor building floors or all the way up to the roof.

A large volume of dirt was removed from each facility. Environmental restoration objectives required that all basin dirt and contaminated soil to a depth of about fifteen feet be removed. Conveniently, Hanford operates a large open pit burial facility that could accept the dirt. However, disposal criteria consequently applied which the dirt shipments had to meet. To ensure the criteria was not exceeded, contaminated dirt was mixed with clean dirt dug up from elsewhere, which reduced the load's activity to permissible levels. Mixing was done by placing the excavated dirt in a skiff (a small hopper) and surveying it with an RO-7 radiac. Clean dirt was then added as necessary to meet the burial site's criteria. The skiff was then dumped into a trailer hopper and transported to the disposal facility by truck.

Personnel entry into the basins was held to a minimum. Generally, entries were needed only for special purposes--to clean out small areas the BROKK could not reach, for special tasks (pumping out rain water), or to assist in recovering irradiated fuel pins. Most actions could be done without actual entry, with the workers operating out of a JLG man-lift using long handled tools. The man-lift had a reach of 85 feet, which covered about half of the basin.

In the end, 17 irradiated fuel pins were found and recovered in the F storage basin. This was the biggest surprise of the ISS program, to date. The safety analysis estimated five pins would be found. Anticipating that more would be, the ASA controls stipulated how many pins could be removed without first requiring DOE review (not approval) of the removal operation. This strategy worked well, and the contractor notified DOE each time further permission was required. The major concern was criticality inside the pin storage cask and radiation hazard to the field workers, who handled the pins with extension tools. The pins were successfully removed and transported to an operating fuel storage basin and disposed of as part of a separate cleanup program.

Working space inside the reactors was often cramped.

Two cranes were essential to the job. One would not have sufficed. The reactor building elevator's concrete counterweights (25,000 pound apiece) were the heaviest, most difficult lift of the program. The track-hoe excavator (BROKK) with its shears, hammer, and bucket was the most useful D&D tool.

Another surprise was the number of birds found nesting in the facilities, including the large predator great horned owl.

For long term storage, installation of the new roof was the single most important measure. The caulking used in the joints could be a concern in the coming decades. The caulk used had a 50-year guarantee, but it may not live up to the warranty. Storm damage may also be a concern. Corrosion should be minimal, and the fasteners are compatible with the original steel. Special attention was given to where runoff would occur from the roof, ensuring it was directed well away from the reactor block area.

The remaining shield walls to which the roof was anchored were sometimes found out of square or out of plumb. As a result, the dimensions to the new steel trusses had to be modified.

Throughout the D&D period, cuts and adjustments occurred to ISS funding. Because five reactors were simultaneously at different stages in D&D (all the way from completing the ASA and conducting the initial rad surveys at one, to tightening the roof fasteners at another), cuts in one area were accommodated by shifting work back and forth among the facilities, without a major perturbation to the overall program. Thus, the work force remained reasonably constant and work proceeded steadily.

Figure Four shows an Interim Safe Storage enclosure surrounding the C Reactor block. Note the dramatic decrease in facility footprint.

Lessons Learned from D&D/ISS

1. Be extremely cautious in accepting information from any records or analysis more than 10 years old. Prints, records, or logs from the AEC/DOE production period, 1944-1989--including design information--had notoriously poor quality and no configuration control to speak of.

2. Question glib assertions from any source that blithely declare that radiologic inventory of old facilities is known to three significant figures.

3. Once initial surveys are made and the extent of the radiation hazard is known, hit decon hard before anything else is done. Preferably, remove as much contamination as possible. Securely fix the rest. Don't assume fixing paint won't peel. Decon can always use more manpower and money, up front. Aggressive early decontamination will keep workers out of protective clothing later on. The recovered work efficiencies and savings in laundry services will pay for the effort several times over.

4. Keep the safety analysis flexible to accommodate surprises, (like the number of irradiated fuel pins buried in a storage basin) but rigid enough to handle them safely.

5. The most serious worker hazard is falling. Cave-in's and collapses are particularly insidious. Implement an aggressive fall protection program immediately.

6. Lightning protection is not needed (at least in the mid-Columbia). Compliance with modern lightning standards can be extremely difficult in older facilities.

7. Keep track of lessons-learned from other facilities. Take the time to document them, after talking with all parties (supervision and crafts) involved. Then, read them before starting the next job.

8. Don't use existing wiring or electrical systems. Run new wire in new conduits.

9. The best tool to avoid cost escalation during D&D is fixed price contracting. This, of course, forces the bidder to assume some risk for unknown contaminants. Life is unfair.

10. Be certain the end state is known and agreed to before D&D work begins. The environmental ROD (or similar decision) must clearly state the final facility condition (what will be removed, and what will remain at the end) before the first survey swipe is taken.

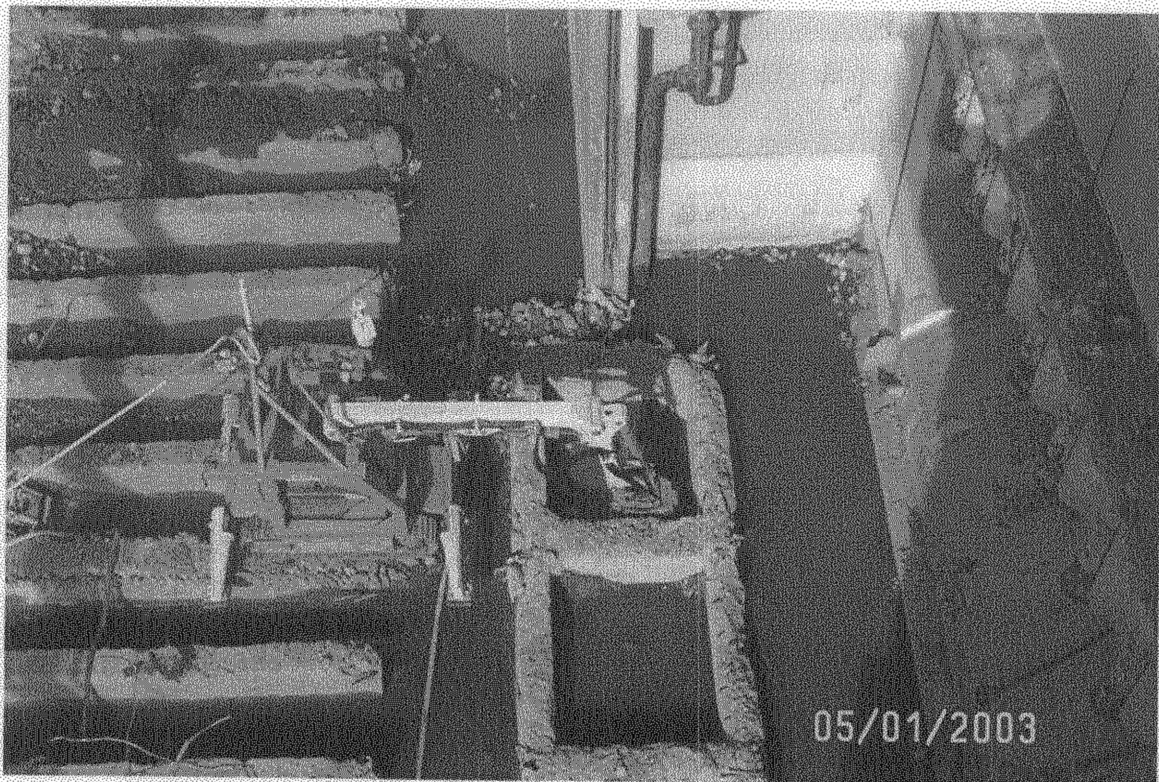
Conclusions

As of May, 2003, C and DR Reactors at Hanford have been fully placed into interim safe storage with the safe storage enclosure completed. D Reactor is nearly complete as well. F Reactor will be completed in August, 2003. Work continues at H Reactor.

Last December, five years after C Reactor was successfully cocooned, the first inspection was made of a reactor block placed into ISS. No degradation was found, except for a small area of the roof flashing that required repair. To document conditions, the inspection team used a high resolution digital camera that, when combined with a new software system, creates 360-degree photos of the area viewed. The images allow a virtual tour, where the remote viewer can zoom in on selected areas which are visible from multiple angles. The photos can be used to compare future changes to existing conditions.

Inspection results showed that an SSE creates a safe and environmentally secure structure for a reactor block that will significantly reduce surveillance and maintenance expenses. Thus, the ISS concept worked. DOE is now considering lengthening the inspection period of ISS to ten years, which would reduce surveillance costs even more.

FIGURE THREE



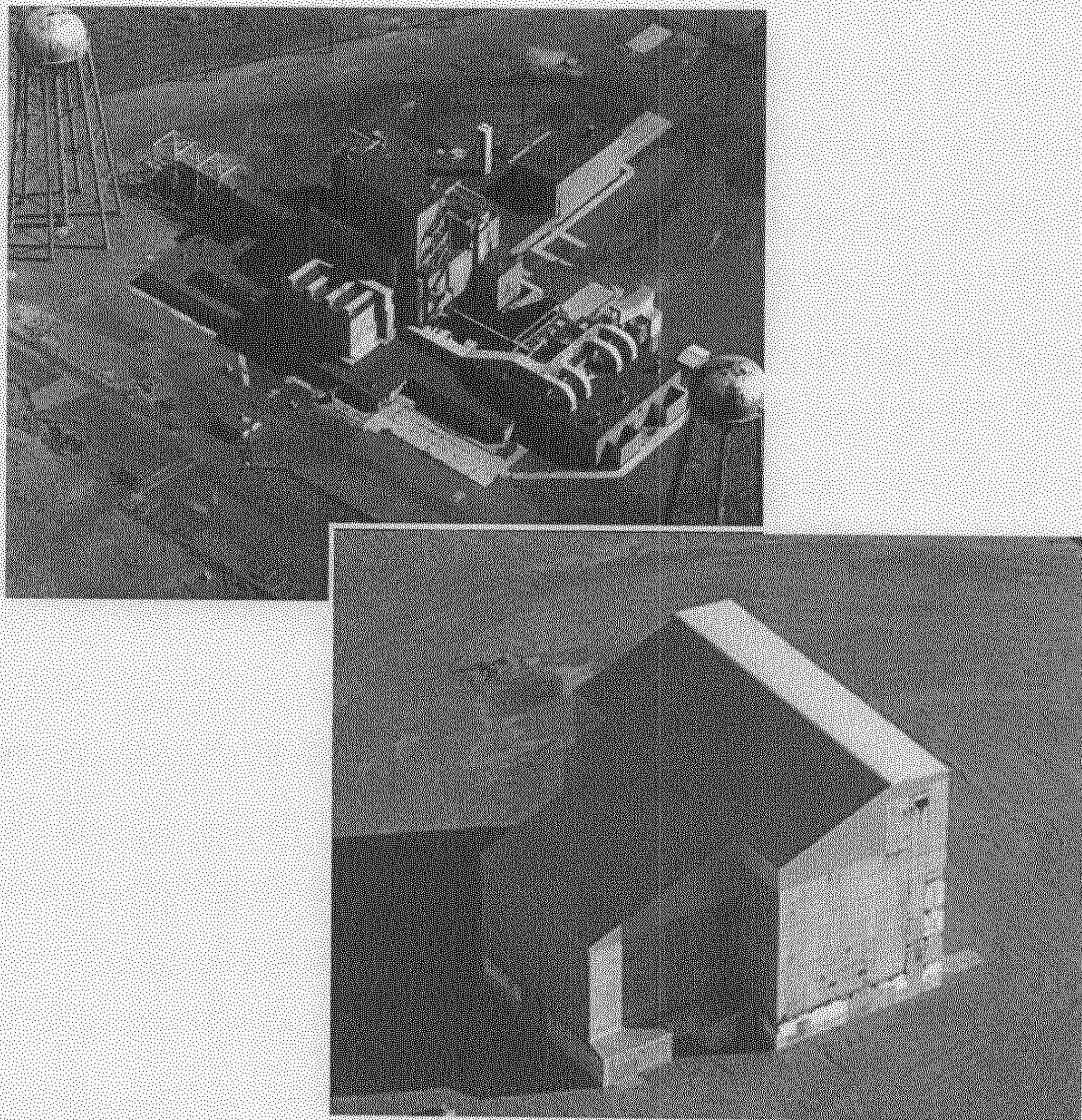


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FIGURE FOUR

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